JOURNAL OF QUATERNARY SCIENCE (2014) 29(4) 370–380 ISSN 0267-8179. DOI: 10.1002/jqs.2710

A ^{10}Be chronology of south-western Scandinavian Ice Sheet history during the Lateglacial period

JASON P. BRINER,[1]* JOHN INGE SVENDSEN,[2] JAN MANGERUD,[2] ØYSTEIN S. LOHNE[2] and NICOLÁS E. YOUNG[3]

[1]Department of Geology, University at Buffalo, Buffalo, NY 14260, USA

[2]Department of Earth Science, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway

[3]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA

Received 22 December 2013; Revised 12 March 2014; Accepted 29 March 2014

ABSTRACT: We present 34 new cosmogenic ^{10}Be exposure ages that constrain the Lateglacial (Bølling–Preboreal) history of the Scandinavian Ice Sheet in the Lysefjorden region, south-western Norway. We find that the classical Lysefjorden moraines, earlier thought to be entirely of Younger Dryas age, encompass three adjacent moraines attributed to at least two ice sheet advances of distinctly different ages. The ^{10}Be age of the outermost moraine (14.0 ± 0.6 ka; $n = 4$) suggests that the first advance is of Older Dryas age. The innermost moraine is at least 2000 years younger and was deposited near the end of the Younger Dryas (11.4 ± 0.4 ka; $n = 7$). After abandonment of the innermost Lysefjorden Moraine, the ice front receded quickly towards the head of the fjord, where recession was interrupted by an advance that deposited the Trollgaren Moraine at 11.3 ± 0.9 ka ($n = 5$). ^{10}Be ages from the inboard side of the Trollgaren Moraine suggest final retreat by 10.7 ± 0.3 ka ($n = 7$). The late culmination of the Younger Dryas advance contrasts with other sectors of the Scandinavian Ice Sheet where the margin appears to have culminated earlier during the Younger Dryas stadial, followed by retreat during the middle and late part of the Younger Dryas. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: Allerød; ^{10}Be dating; Lateglacial; Scandinavian Ice Sheet; Younger Dryas.

Introduction

The demise of late Pleistocene ice sheets during the last deglaciation offers lessons about how ice sheets respond to climate change. For example, the spatial expression of ice sheet change during the last deglaciation around the globe reveals the interhemispheric complexity of the climate system (e.g. Clark *et al.*, 2009). Furthermore, the response of ice sheets to short-lived climate perturbations superimposed on overall deglaciation provides insight into ice sheet sensitivity to abrupt climate change (e.g. Lohne *et al.*, 2007; Young *et al.*, 2011). Finally, the pattern of retreat in fjords versus land-based ice margins can be used to elucidate local and external controls on ice margin changes (e.g. Briner *et al.*, 2009; Mangerud *et al.*, 2013). Embedded within the pattern of complete ice sheet disappearance from North America and Scandinavia is a detailed archive of ice sheet response during the climatically turbulent Lateglacial period (~15–10 ka). The behavior of the Scandinavian Ice Sheet, in particular, is tightly linked to ocean circulation and climate change of the adjacent North Atlantic Ocean (Vorren and Plassen, 2002; Mangerud *et al.*, 2013), an important epicenter of deglacial climate change (Clark *et al.*, 1999). However, reconstructing accurate ice sheet histories relies on a combination of detailed field mapping, careful stratigraphy and robust ice margin chronologies. The last of these is the main objective of this study.

The most widely traceable moraines around the Scandinavian Ice Sheet (Fig. 1) date to the Younger Dryas period (12.7–11.6 ka; Lohne *et al.*, 2013). However, the precise timing of when the glacial advance culminated varies throughout Scandinavia (Mangerud, 1980). In most locations, the maximum ice extent was achieved in the early or middle Younger Dryas (Andersen *et al.*, 1995; Vorren and Plassen, 2002; Olsen *et al.*, 2013). However, in the Bergen–Hardangerfjorden area, the maximum ice extent was reached at the end of the Younger Dryas (Bondevik and Mangerud, 2002; Lohne *et al.*, 2012; Mangerud *et al.*, 2011). Furthermore, in some places the ice margin re-advanced tens of kilometers through deep fjords during the Younger Dryas, whereas other ice margin sectors experienced standstills, and yet others were retreating (Reite, 1994; Mangerud *et al.*, 2011). The underlying cause for asynchronous ice sheet fluctuations during the Younger Dryas remains unclear, although varying ice margin response time due to topography, ice-sheet configuration and precipitation patterns have been proposed (Mangerud, 1980; Mangerud *et al.*, 2011).

In south-western Norway, prominent moraine complexes can be interconnected to outline an ice margin that terminated at the mouths of the many fjords that feed into Boknafjorden (Fig. 2; Andersen, 1954). To the south-east of Boknafjorden lies Lysefjorden, a deeply carved ~40-km-long fjord with a prominent end moraine at its mouth that splits into a sequence of moraines in the mountains north of the fjord (Fig. 3). The moraine system (termed the Lysefjorden moraines) extends north and south of Lysefjorden, and is considered of Younger Dryas age (Andersen, 1954; Blystad and Selsing, 1988). A younger moraine, named the Trollgaren Moraine, is mapped across a mountain plateau ~20 km to the east of the Lysefjorden Moraine at the mouth of Jøsenfjorden (Andersen, 1954; Anundsen, 1972; Blystad and Selsing, 1988). Another moraine system, which is correlated with the Trollgaren Moraine, is mapped in the mountainous areas near the head of Lysefjorden (Andersen, 1954). These sharp-crested ridges can be traced over many kilometers, but they are smaller and narrower than most of the Lysefjorden moraines mentioned above, and they cannot be traced continuously between the individual fjord systems.

Here, we use cosmogenic ^{10}Be exposure dating (hereafter ^{10}Be dating) to determine: (i) the timing of ice recession outboard of the Lysefjorden moraines, (ii) the age range contained within the Lysefjorden moraines, (iii) the age of the Trollgaren Moraine system and (iv) the final ice sheet retreat to the ice divide in south-central Norway.

*Correspondence: Jason P. Briner, as above.
E-mail: jbriner@buffalo.edu

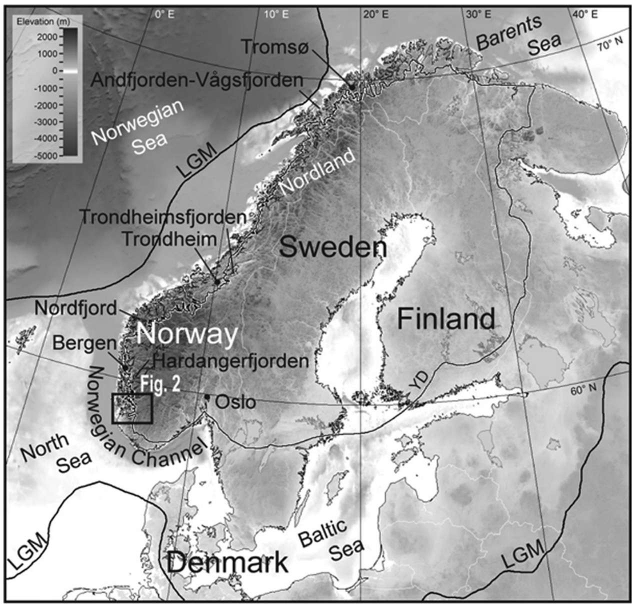

Figure 1. Map showing the extent of the Scandinavian Ice Sheet during the Last Glacial Maximum (LGM) and Younger Dryas (YD). From Mangerud *et al.* (2011).

Setting and methods

In south-western coastal Norway, ice flow from an ice divide located along the mountainous spine of south-central Norway merged with the Norwegian Channel Ice Stream along the western coastline (e.g. Sejrup *et al.*, 1998; Fig. 1). During the Last Glacial Maximum the ice margin was located along the continental shelf break. At the onset of deglaciation the ice front first retreated up (i.e. southwards) the Norwegian Channel and subsequently inland (i.e. eastwards) leaving a rim of ice-free area along the coast (Mangerud *et al.*, 2011). The deglaciation of the coastal lowland of Jæren (Fig. 2) took place 16–17 cal ka BP (Knudsen, 2006). After this time, the ice front receded farther inland and eventually deposited a series of moraines in the Lysefjorden area (Fig. 2). The absolute chronology of the deglaciation is generally poor; however, there are a few radiocarbon constraints and also sea-level constraints. Blystad and Anundsen (1983) outline a glacial history that depicts an ice sheet advance culminating ~14.2 cal ka BP (radiocarbon ages from Blystad and Anundsen (1983) and Blystad and Selsing (1988) were calibrated using CALIB 7.0 and the IntCal13 calibration curve), followed by retreat and a subsequent re-advance between ~13.0 and 12.7 cal ka BP (Fig. 4). The age of this late Allerød or early Younger Dryas advance is constrained by radiocarbon ages on shells reworked into a till and above this till that was deposited just beyond the Lysefjorden Moraine at the mouth of Jøsenfjorden (Fig. 2). Furthermore, Anundsen (1977) described a till 3–4 km beyond the main Lysefjorden Moraine in the northern Boknafjorden area that was considered late Allerød or earliest Younger Dryas in age. An updated glaciation (time–distance) curve suggests a middle Younger Dryas age of the Lysefjorden moraines (Andersen *et al.*, 1995). Blystad and Selsing (1988) obtained basal radiocarbon ages from bogs between and inland of the Lysefjorden and Trollgaren moraines, suggesting that ice had retreated from the Lysefjorden Moraine as early as $\sim 11.7 \pm 0.4$ cal ka BP, and from the Trollgaren Moraine before $\sim 11.0 \pm 0.2$ cal ka BP. Although this chronology outlines the general pattern of multiple ice sheet advances (Fig. 4), the ages were derived from bulk sediments and, ultimately, existing ages remain few and far between.

To improve constraints on the timing of ice retreat and moraine deposition, we collected samples for ^{10}Be dating (Fig. 5) from four main areas (Fig. 2). The first area is along Lysefjorden. We sampled bedrock and erratic boulders from a bedrock hill ~100 m above sea level (a.s.l.) and ~3.5 km beyond (north-west of) the Lysefjorden Moraine at the mouth of the fjord (Fig. 3). We also collected a sample from striated bedrock immediately inboard of the Lysefjorden Moraine at the fjord mouth, not far from the classic Esmark (Vassryggen) Moraine (Worsley, 2006). We also collected samples of ice-eroded bedrock from 9 and 24 km up fjord. Finally, we collected a series of samples (from bedrock and from erratic boulders perched on bedrock) at the head of Lysefjorden.

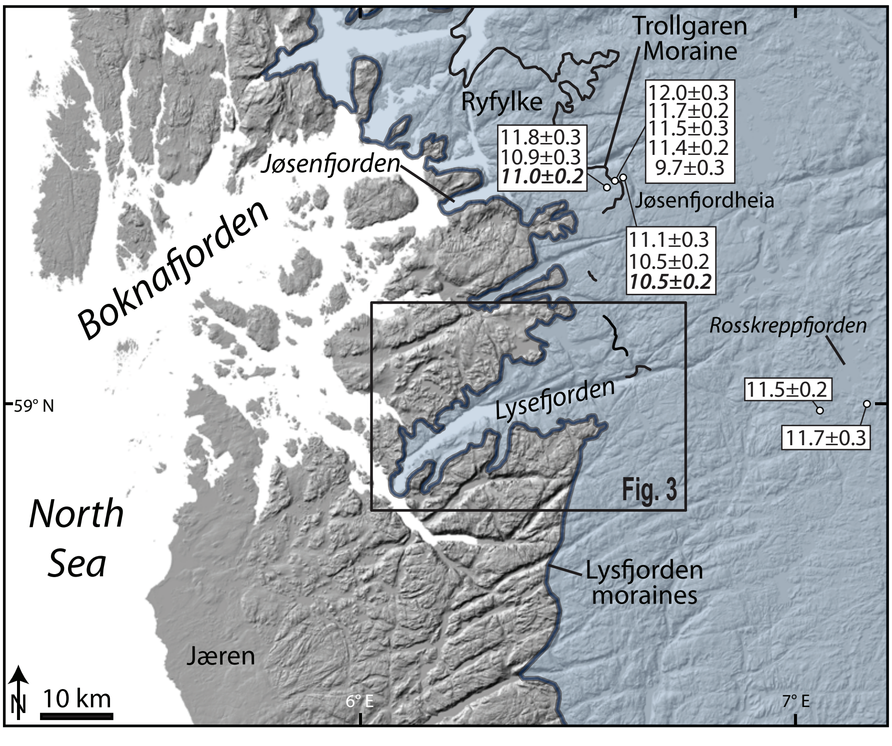

Figure 2. Map of the Boknafjorden region showing the extent of the Scandinavian Ice Sheet corresponding to the Lysefjorden Moraine (thick line and ice colored blue) and Trollgaren Moraine (thin line), according to Andersen (1954) south of Jøsenfjorden and Anundsen (1972) north of this fjord. Numbers in white boxes are cosmogenic ^{10}Be exposure ages (ka); ages in plain text are from boulders, and ages in bold, italic text are from bedrock surfaces.

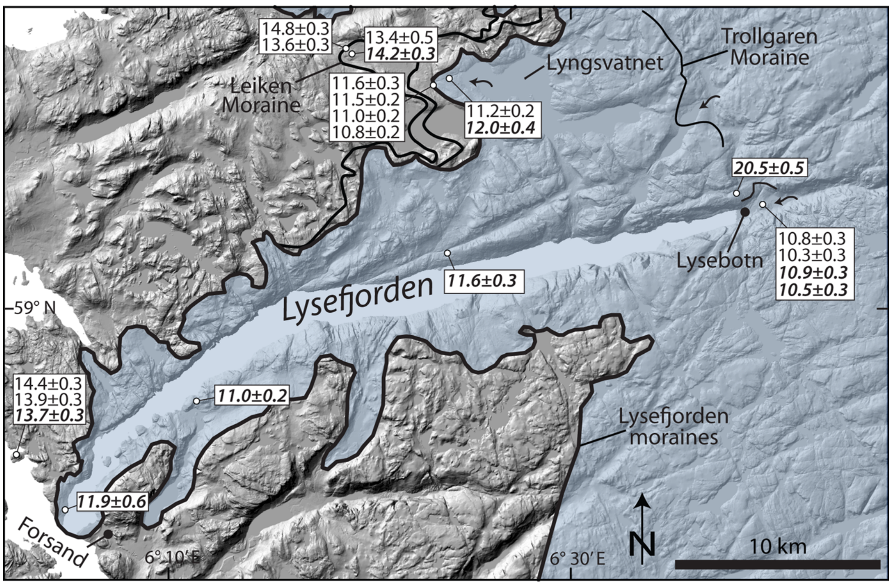

Figure 3. The Lysefjorden (thick lines) and Trollgaren moraines (thin line), re-drawn from Andersen (1954). The extent of the Scandinavian Ice Sheet during formation of the youngest Lysefjorden moraine is colored blue. Numbers in white boxes are cosmogenic ^{10}Be exposure ages (ka); ages in plain text are from boulders, and ages in bold, italic text are from bedrock surfaces. Note that we have named the outermost moraine the Leiken Moraine, and we no longer consider it as belonging to the Lysefjorden moraine complex.

The second area is a broad valley ~500–700 m a.s.l. downstream of the large lake Lyngsvatnet (685 m a.s.l) on the northern side of the fjord. Here, Andersen (1954) mapped three prominent moraines crossing the valley floor, with 5 km between the outermost and innermost moraines (Fig. 3). The outer two moraines are crosscut by the inner moraine, which is the only moraine present at the mouth of Lysefjorden, revealing that the latter was deposited during a re-advance. From this valley, we collected samples from moraine boulders on the outermost and innermost moraines, and from erratic boulders and striated bedrock just inboard of the outermost and innermost moraines.

The third area where we collected samples for ^{10}Be dating is on the Jøsenfjordheia plateau at ~800 m a.s.l. (Fig. 2). Here, we sampled boulders from the Trollgaren Moraine type locality (Andersen, 1954; Fig. 5), and from erratic boulders and striated bedrock on both sides of the moraine ridge. Trollgaren Moraine is a well-defined, long and narrow ridge that for the most part is composed of a pile of boulders, presumably pushed by an ice sheet advance that terminated at this position. Finally, the fourth area is the inner mountainous region of south-central Norway, where we collected two erratic boulders near the large lake Rosskreppfjorden to constrain the timing of final ice disappearance (Fig. 2).

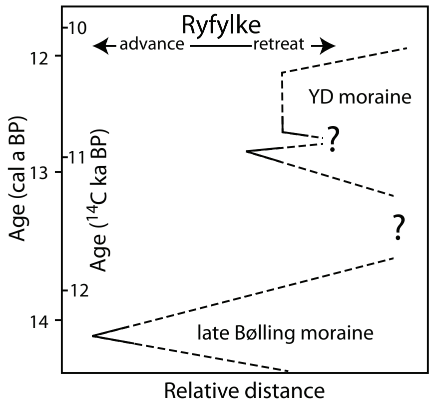

Figure 4. Time–distance diagram for the Scandinavian Ice Sheet in the Ryfylke region (shown in Fig. 2); from Blystad and Anundsen (1983).

We sampled the top several centimeters of boulder and bedrock surfaces using a hammer and chisel. We sampled mostly flat surfaces and avoided edges, and used a clinometer to measure topographic shielding and a hand-held GPS receiver to record sample location and elevation. Sample elevations range from ~69 to 1067 m a.s.l. and all samples were collected from above the local marine limit, which is ~35 m a.s.l. at the mouth of Lysefjorden, and estimated to be ~60 m a.s.l. at the head of the fjord (Andersen, 1954; Anundsen, 1985). All samples were prepared for ^{10}Be analysis at the University at Buffalo Cosmogenic Nuclide Laboratory. Following crushing, sieving and quartz isolation, samples were digested and beryllium was isolated following procedures previously described (Young *et al.*, 2013a). Each sample batch included one process blank; all samples were spiked with ~250–290 μg of ^{9}Be carrier. Sample ^{10}Be/^{9}Be ratios were measured at the Center for Mass Spectrometry, Lawrence Livermore National Laboratory and normalized to standard 07KNSTD3110 with a reported ratio of 2.85×10^{-12} (Nishiizumi *et al.*, 2007; Rood *et al.*, 2010). Procedural blank ratios were 9.6×10^{-16}, 9.6×10^{-16}, 1.2×10^{-15}, 1.2×10^{-15} and 1.8×10^{-15}, equating to background corrections of 0.3–1.6% of the sample total. One-sigma analytical uncertainties on background-corrected samples range from 1.9 to 5.1% and average 2.5 ± 0.7% (Table 1).

The ^{10}Be ages were calculated using the CRONUS-Earth online exposure age calculator (Balco *et al.*, 2008; version 2.2.1; hess.ess.washington.edu/). We adopted a locally constrained production rate previously reported from southwestern Norway (Goehring *et al.*, 2012a,b) with the Lal/Stone constant-production scaling scheme to calculate ^{10}Be ages (Lal, 1991; Stone, 2000). We discuss ages calculated with this production rate versus the Arctic-wide ^{10}Be production rate (Young *et al.*, 2013b; ~4% lower) in the Discussion. We use the Lal/Stone constant-production scaling scheme because the influence of the Earth's magnetic field on ^{10}Be production rate is negligible at the study area's high latitude (°59N; Gosse and Phillips, 2001); however, use of alternative scaling schemes results in ^{10}Be ages that vary by up to ~4%. The CRONUS-Earth calculator makes sample specific corrections for latitude, elevation, sample thickness and sample density (Table 1). Reported age uncertainties for individual samples reflect one sigma accelerator mass spectrometry (AMS) uncertainty only ('internal' uncertainty reported from the

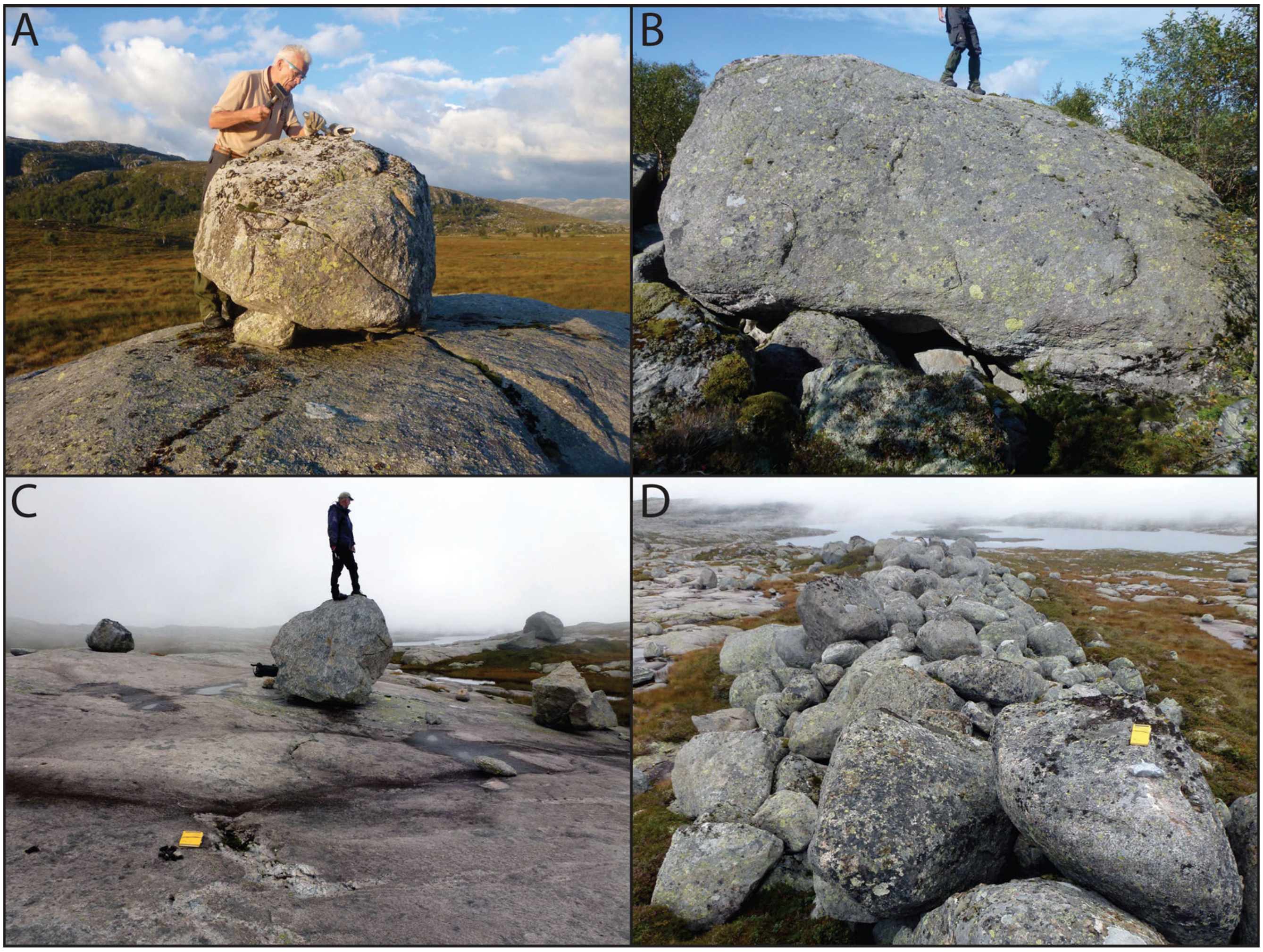

Figure 5. Photographs of samples for cosmogenic ^{10}Be exposure dating. (A) 11NOR-27 (13.4 ± 0.5 ka), collected from a site located immediately inboard of the Leiken Moraine near Lyngsvatnet. (B) 11NOR-15 (11.5 ± 0.2 ka), collected from the inner moraine of the Lysefjorden moraine near Lyngsvatnet. (C) 11NOR-70 (boulder, 10.5 ± 0.2 ka) and 11NOR-71 (bedrock sample by field book, 10.5 ± 0.2 ka), collected from inside of the Trollgaren moraine. (D) Trollgaren moraine; field book on sample 11NOR-65 (11.4 ± 0.2 ka) for scale.

CRONUS-Earth website). We made no corrections for surface erosion or shielding by snow cover. The crystalline bedrock in the region is resistant to erosion, and glacial striations were observed at most sampling sites. The field area has undergone isostatic adjustment since deglaciation, and the sample elevation at the time of collection does not reflect its time-averaged sample elevation history. However, the influence of isostatic uplift on the ^{10}Be ages is probably offset by unquantifiable effects of atmospheric pressure changes related to ice sheet proximity and glacial-world atmospheric compression (Staiger *et al.*, 2007). The ages we report in the text below are not adjusted for isostatic uplift, but we report both 'raw' and 'uplift-corrected' ages in Table 1. For the uplift-corrected ages, we use relative sea-level data from Anundsen (1985). Note that ^{10}Be ages corrected for isostatic uplift are ~0.9–1.4% older than the uncorrected ages, and thus the correction does not significantly influence our chronology.

Results

The ^{10}Be ages range from 14.8 ± 0.3 to 9.7 ± 0.3 ka, with the exception of a single older ^{10}Be age of 20.5 ± 0.5 ka (Figs 2, 3 and 6; Table 1). Beyond the Lysefjorden Moraine at the fjord mouth, two erratic boulders and one ice-sculpted bedrock site have ^{10}Be ages of 14.4 ± 0.3, 13.9 ± 0.3 and 13.7 ± 0.3 ka (Fig. 3), respectively, and average 14.0 ± 0.4 ka. Four ice-sculpted bedrock samples collected along Lysefjorden are 11.9 ± 0.6 ka (immediately inboard of the Lysefjorden Moraine), 11.0 ± 0.2 ka (9 km from the fjord mouth), 11.6 ± 0.3 ka (24 km from the fjord mouth) and 20.5 ± 0.5 ka (just outside of the Trollgaren Moraine near Lysebotn). Just inboard of the moraines near the head of Lysefjorden (Lysebotn) believed to correlate with the Trollgaren Moraine, two samples from ice-sculpted bedrock and two samples from erratic boulders perched on bedrock all overlap; the ^{10}Be ages range from 10.8 ± 0.3 to 10.3 ± 0.3 ka (Fig. 3) and average 10.6 ± 0.3 ka.

Two moraine boulders from the most ice-distal moraine in the Lyngsvatnet area yield ^{10}Be ages of 14.8 ± 0.3 and 13.6 ± 0.3 ka (Fig. 3). Within ~100 m inboard of the moraine, an erratic boulder perched on bedrock and an ice-sculpted bedrock sample yield ^{10}Be ages of 13.4 ± 0.5 and 14.2 ± 0.3 ka, respectively. All four ^{10}Be ages from this outermost moraine site statistically overlap, and together average 14.0 ± 0.6 ka (see interpretation below). [Andersen (1954) included all ridges in the Lyngsvatn area in a complex that he called the 'Lysefjorden Stage moraines'. Realizing that the mapped ridges have different ages, we now label the outermost moraine the Leiken Moraine and restrict the term Lysefjorden Moraine to the moraine crossing the mouth of Lysefjorden and its correlatives.] The most ice-proximal

Table 1. Sample data and ^{10}Be ages (Mean ages ± 1 SD)

Sample	Sample type	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Sample thickness (cm)	Topographic shielding factor	^{10}Be concentration (atoms/g)	^{10}Be age (ka)*	Corrected for uplift†	Arctic-wide PR‡
Beyond Lysefjorden										
42-11NOR-31	Boulder	58° 56.002′	6° 2.018′	104	2	1	68 225.2 ± 1403.3	14.4 ± 0.3	14.6 ± 0.3	14.9 ± 0.3
42-11NOR-30	Boulder	58° 56.020′	6° 1.843′	108	2	1	66 146.5 ± 1459.6	13.9 ± 0.3	14.1 ± 0.3	14.4 ± 0.3
42-11NOR-29	Bedrock	58° 56.052′	6° 1.971′	113	1	1	66 024.2 ± 1487.2	13.7 ± 0.3	13.9 ± 0.3	14.2 ± 0.3
Mean ages ± SD								14.0 ± 0.4	14.2 ± 0.4	14.5 ± 0.4
Leiken moraine										
45-11NOR-24	Boulder	59° 7.322′	6° 18.221′	447	2.5	0.998	97 098.7 ± 1946.2	14.8 ± 0.3	14.9 ± 0.3	15.3 ± 0.3
44-11NOR-23	Boulder	59° 7.357′	6° 18.307′	466	4	0.998	89 957.3 ± 1962.3	13.6 ± 0.3	13.7 ± 0.3	14.1 ± 0.3
45-11NOR-27	Boulder	59° 7.155′	6° 18.637′	457	1	0.998	90 030.8 ± 3113.7	13.4 ± 0.5	13.5 ± 0.5	13.8 ± 0.5
44-11NOR-25	Bedrock	59° 7.313′	6° 18.385′	457	2	0.998	94 902.2 ± 1786.3	14.2 ± 0.3	14.4 ± 0.3	14.7 ± 0.3
Mean ages ± SD								14.0 ± 0.6	14.1 ± 0.6	14.5 ± 0.6
Lysefjorden transect										
42-11NOR-39	Bedrock	58° 54.718′	6° 4.446′	69	1.5	0.999	54 386.3 ± 2781.6	11.9 ± 0.6	12.0 ± 0.6	12.3 ± 0.6
42-11NOR-22	Bedrock	59° 1.865′	6° 23.979′	288	4	0.997	64 733.6 ± 1419.8	11.6 ± 0.3	11.7 ± 0.3	12.0 ± 0.3
42-11NOR-40	Bedrock	58° 57.682′	6° 11.173′	109	3	0.989	51 295.4 ± 1005.1	11.0 ± 0.2	11.1 ± 0.2	11.3 ± 0.2
42-11NOR-42	Bedrock	59° 3.936′	6° 38.967′	405	2	0.989	128 563.5 ± 2974.4	20.5 ± 0.5	19.9 ± 0.5	21.2 ± 0.5
Lysebotn										
46-11NOR-44	Boulder	59° 3.539′	6° 40.175′	80	1	0.98	49 140.1 ± 1547.5	10.8 ± 0.3	10.9 ± 0.3	11.1 ± 0.4
46-11NOR-46	Bedrock	59° 3.528′	6° 40.106′	89	1.5	0.98	48 304.2 ± 1341.3	10.5 ± 0.3	10.7 ± 0.3	10.9 ± 0.3
42-11NOR-45	Bedrock	59° 3.550′	6° 40.162′	96	1	0.98	50 733.0 ± 1172.9	10.9 ± 0.3	11.1 ± 0.3	11.3 ± 0.3
42-11NOR-47	Boulder	59° 3.517′	6° 40.115′	89	3.5	0.98	46 346.6 ± 1240.1	10.3 ± 0.3	10.4 ± 0.3	10.6 ± 0.3
Mean ages ± SD								10.6 ± 0.3	10.8 ± 0.3	11.0 ± 0.3
Inner Lysefjorden moraine										
45-11NOR-13	Boulder	59° 6.218′	6° 23.122′	593	1	0.999	88 580.6 ± 2184.7	11.6 ± 0.3	11.7 ± 0.3	12.0 ± 0.3
45-11NOR-15	Boulder	59° 6.275′	6° 23.091′	591	3	1	86 399.8 ± 1715.2	11.5 ± 0.2	11.6 ± 0.2	11.9 ± 0.2
44-11NOR-14	Boulder	59° 6.218′	6° 23.122′	593	2.5	1	83 182.1 ± 1649.4	11.0 ± 0.2	11.1 ± 0.2	11.4 ± 0.2
44-11NOR-12	Boulder	59° 6.043′	6° 23.939′	715	1.5	1	91 682.1 ± 1821.0	10.8 ± 0.2	10.9 ± 0.2	11.2 ± 0.2
44-11NOR-20	Bedrock	59° 6.475′	6° 23.123′	603	1.5	1	91 913.4 ± 3074.5	12.0 ± 0.4	12.1 ± 0.4	12.4 ± 0.4
44-11NOR-17	Boulder	59° 6.600′	6° 23.903′	684	2	1	91 806.3 ± 1730.7	11.2 ± 0.2	11.3 ± 0.2	11.6 ± 0.2
Mean ages ± SD								11.4 ± 0.4	11.5 ± 0.4	11.8 ± 0.4
Beyond Trollgaren moraine										
46-11NOR-73	Boulder	59° 17.628′	6° 34.534′	863	1	0.999	114 591.8 ± 2464.4	11.8 ± 0.3	12.0 ± 0.3	12.3 ± 0.3
46-11NOR-74	Bedrock	59° 17.635′	6° 34.551′	863	1	0.999	105 561.3 ± 2281.9	10.9 ± 0.2	11.1 ± 0.2	11.3 ± 0.2
46-11NOR-75	Boulder	59° 17.593′	6° 34.395′	849	3	0.999	103 594.3 ± 2857.2	11.0 ± 0.3	11.2 ± 0.3	11.4 ± 0.3
Mean ages ± SD								11.3 ± 0.5	11.4 ± 0.5	11.6 ± 0.5
Trollgaren moraine										
45-11NOR-64	Boulder	59° 18.026′	6° 34.706′	770	1	0.999	106 233.0 ± 2317.9	12.0 ± 0.3	12.1 ± 0.3	12.4 ± 0.3
45-11NOR-63	Boulder	59° 18.043′	6° 34.617′	775	1	0.999	104 296.7 ± 2069.2	11.7 ± 0.2	11.9 ± 0.2	12.1 ± 0.2
46-11NOR-66	Boulder	59° 18.011′	6° 34.748′	779	1	0.999	103 262.3 ± 3008.6	11.5 ± 0.3	11.6 ± 0.3	11.9 ± 0.3
46-11NOR-65	Boulder	59° 18.014′	6° 34.740′	779	2.5	0.999	101 718.4 ± 1962.6	11.4 ± 0.2	11.6 ± 0.2	11.8 ± 0.2
44-11NOR-62	Boulder	59° 18.056′	6° 34.551′	776	3	0.998	85 579.8 ± 2503.0	09.7 ± 0.3	09.8 ± 0.3	10.0 ± 0.3
Mean ages ± SD								11.3 ± 0.9	11.4 ± 0.9	11.6 ± 0.9
Inside Trollgaren moraine										
46-11NOR-69	Boulder	59° 18.086′	6° 35.282′	787	1	0.999	100 909.6 ± 2989.5	11.1 ± 0.3	11.3 ± 0.3	11.5 ± 0.3
46-11NOR-70	Boulder	59° 18.114′	6° 35.380′	792	1	0.999	95 950.1 ± 2150.1	10.5 ± 0.2	10.7 ± 0.2	10.9 ± 0.2
46-11NOR-71	Bedrock	59° 18.114′	6° 35.380′	791	2	0.999	94 707.6 ± 1976.3	10.5 ± 0.2	10.6 ± 0.2	10.9 ± 0.2
Mean ages ± SD								10.7 ± 0.4	10.9 ± 0.4	11.1 ± 0.4
Inland mountains site										
41-11NOR-49	Boulder	59° 2.013′	7° 13.383′	1067	2	1	133 505.9 ± 2986.2	11.7 ± 0.3	11.9 ± 0.3	12.1 ± 0.3
41-11NOR-50	Boulder	59° 1.625′	7° 5.911′	938	1.5	1	117 665.6 ± 2209.7	11.5 ± 0.2	11.6 ± 0.2	11.9 ± 0.2
Mean ages ± SD								11.6 ± 0.2	11.8 ± 0.2	12.0 ± 0.2

*Western Norway production rate (Goehring *et al.*, 2012a,b). †Western Norway production rate with corrections for isostatic rebound. ‡Arctic-wide production rate (Young *et al.*, 2013b). Notes All samples with a rock density of 2.65 g cm^{-3}; zero rock surface erosion.

moraine in the Lyngsvatnet area corresponds to the Lysefjorden Moraine proper (Andersen, 1954), and four moraine boulders from this ridge have ^{10}Be ages that range from 11.6 ± 0.3 to 10.8 ± 0.2 ka. An erratic boulder perched on bedrock and a bedrock sample from just inboard of the moraine have ^{10}Be ages of 11.2 ± 0.2 and 12.0 ± 0.4 ka, respectively. All six ^{10}Be ages statistically overlap and average 11.4 ± 0.4 ka.

At the Trollgaren Moraine type locality at Jøsenfjordheia, we produced ^{10}Be ages from the moraine and from sites both outboard and inboard of the moraine (Fig. 2). Two erratic boulders perched on bedrock and one sample from ice-sculpted bedrock outboard of the Trollgaren Moraine yield ^{10}Be ages of 11.8 ± 0.3, 10.9 ± 0.3 and 11.0 ± 0.3 ka, respectively, and average 11.3 ± 0.5 ka. Five boulders from the Trollgaren Moraine range from 12.0 ± 0.3 to 9.7 ± 0.3 ka, and average 11.3 ± 0.9 ka. Two erratics perched on ice-sculpted bedrock and one sample from ice-sculpted bedrock inboard of the moraine yield ^{10}Be ages of 11.1 ± 0.3, 10.5 ± 0.2 and 10.5 ± 0.2 ka, respectively, and average

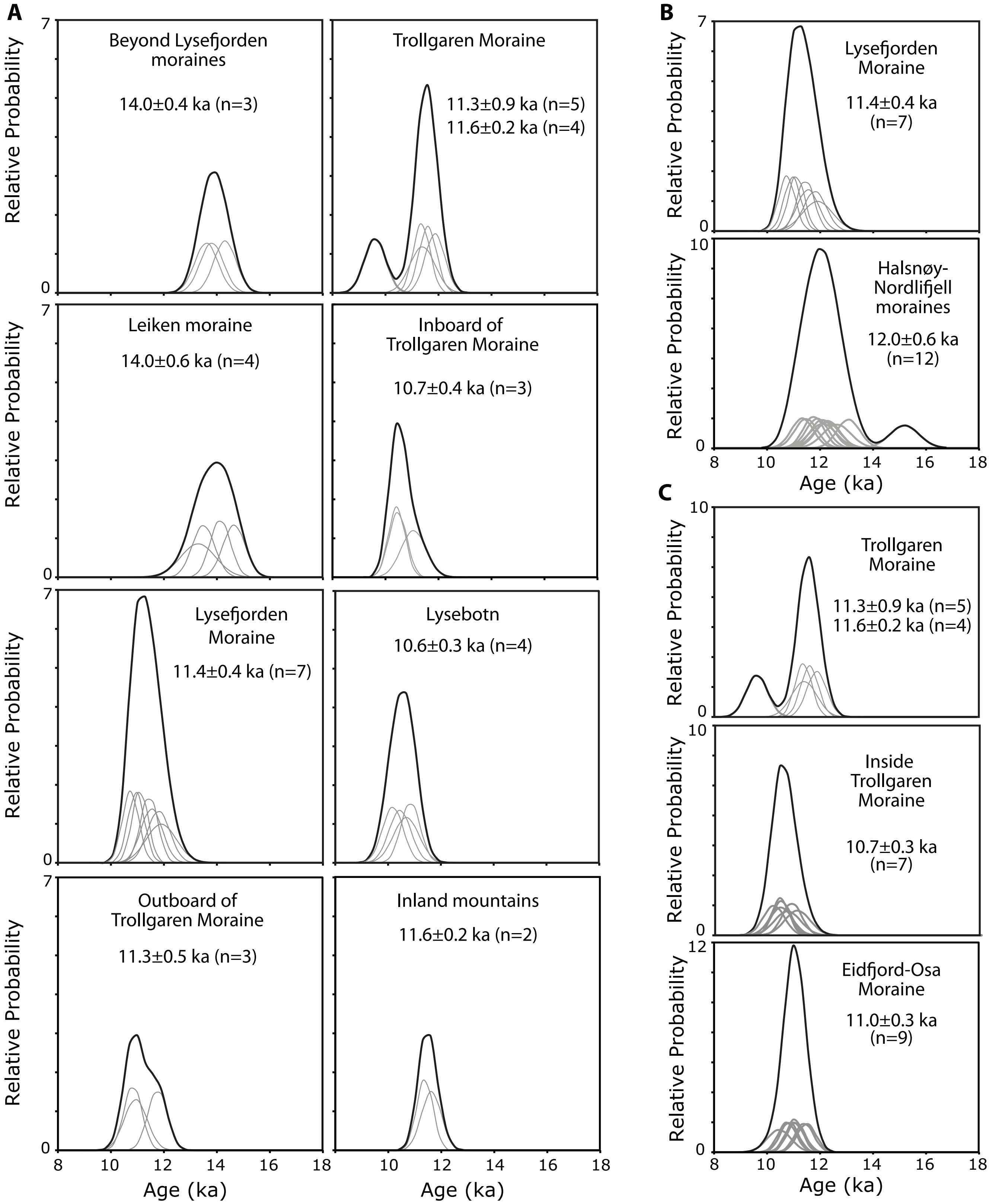

Figure 6. (A) Relative probability plots of age populations from selected sites throughout the field area; thin lines are individual sample ages, black lines are summed probability. Values reported are mean age and one standard deviation uncertainty. (B) Comparison of the ^{10}Be age of the main Lysefjorden Moraine with the ^{10}Be age of the Halsnøy–Nordlifjell moraines in the Hardangerfjorden region (Mangerud *et al.*, 2013). (C) Comparison of ^{10}Be age of the Trollgaren Moraine and sites just inboard with ^{10}Be age of the Eidfjord–Osa Moraine (Mangerud *et al.*, 2013). All ^{10}Be ages were calculated with the same production rate, without corrections for uplift or snow cover, using the CRONUS-Earth website.

10.7 ± 0.4 ka. Finally, in the south-central mountains near the large lake Rosskreppfjorden (Fig. 2), two erratic boulders perched on bedrock yield ^{10}Be ages of 11.7 ± 0.3 and 11.5 ± 0.2 ka, and average 11.6 ± 0.2 ka.

Interpretation of the ^{10}Be ages

We find that the ^{10}Be ages from adjacent boulder and bedrock samples overlap. In almost every case, our bedrock samples are from ice-sculpted sites at relatively low-elevation, valley-bottom locations where glacial erosion was probably significant. There is no obvious evidence for inheritance in our chronology with the single exception of bedrock sample 11NOR-42 (20.5 ± 0.5 ka), which is from 405 m a.s.l. near the head of Lysefjorden (Fig. 3). Although the outcrop from which the sample was collected is striated, it appears that ice did not significantly erode (>2 m) the site during the last glaciation. Decreasing erosional intensity with increasing elevation, and thus increasing inheritance, is typical in fjord landscapes (e.g. Goehring *et al.*, 2008).

We interpret ^{10}Be ages of moraine boulders to represent the culmination of a moraine-building event, and thus to provide the timing of deglaciation from a moraine. Therefore, we combine ^{10}Be ages from moraine boulders with ^{10}Be ages from bedrock and perched erratics located immediately inboard of moraines to provide the best age of moraine abandonment (e.g. Young *et al.*, 2013a). It is our assumption that samples of bedrock from local high points, and from erratics perched directly on debris-free bedrock surfaces, were never covered by sediments.

We have plotted all of our sampling locations from this study onto a single time–distance diagram centered along Lysefjorden (Fig. 7). The average ^{10}Be age of deglaciation outboard of the mouth of Lysefjorden (14.0 ± 0.4 ka) overlaps with the ^{10}Be age for the Leiken Moraine (14.0 ± 0.6 ka). We did not collect samples from the middle moraine in the Lyngsvatnet area, but the samples from the innermost moraine (i.e. the Lysefjorden Moraine) have a mean age of 11.4 ± 0.4 ka, indicating that this moraine is significantly younger than the Leiken Moraine. For this age assignment of the Lysefjorden Moraine, we have combined the ages of boulders on the moraine and from immediately inboard of the moraine near Lyngsvatnet, with the sample (11NOR-39) from immediately inboard of the moraine at the mouth of Lysefjorden.

It is interesting to note that the two ^{10}Be ages of the erratics on the inland mountain site yielded nearly identical ages (11.6 ± 0.2 ka) to the Lysefjorden Moraine ages. However, based on the slope of lateral moraines along Lysefjorden (Andersen, 1954), this mountain plateau must have been covered by thick ice when the Lysefjorden Moraine was abandoned, and thus must have deglaciated later.

The five ^{10}Be ages from the Trollgaren Moraine boulders at Jøsenfjordheia average 11.3 ± 0.9 ka. A similar age (11.3 ± 0.5 ka) was obtained from three erratics resting on the glacially sculptured bedrock surface on the distal side of the moraine ridge. These ages cannot be distinguished from those that were obtained from the Lysefjorden Moraine. However, this area must have been ice covered when the ice sheet occupied the Lysefjorden trough. In contrast to the ages from the Trollgaren Moraine ridge and beyond, three samples that were collected inboard of the moraine yield a slightly younger mean age (10.7 ± 0.4 ka). This may suggest that the ice sheet stabilized in this position for some time. However, based on the morphology (i.e. the very narrow ridge consisting almost only of boulders), we find it unlikely that the ice margin halted at this moraine for a long period. Based on an overall assessment of the series of ages from this area we consider ~11.3 ka to be a reasonable age of the Trollgaren Moraine. The four ^{10}Be ages from the head of Lysefjorden (10.6 ± 0.3 ka) are significantly younger than the Lysefjorden and Trollgaren moraines.

Discussion

The influence of ^{10}Be production rate choice

The time–distance history outlined above is based on an average ^{10}Be production rate value derived from two calibration sites in western Norway (Goehring *et al.*, 2012a,b). However, ^{10}Be production rate research from elsewhere (e.g. Balco *et al.*, 2009), including at several sites in the Arctic (Young *et al.*, 2013b), suggest lower values by ~4% (Table 1). Adopting ^{10}Be ages calculated with the Arctic-wide production rate value shifts the time–distance history of ice margin change earlier by ~4%. While not a significant shift (in most cases the difference is well inside the 1σ AMS measurements error), it leaves open the possibility that the Leiken Moraine (~14.5 ka) pre-dates Termination 1. Furthermore, it would place the innermost Lysefjorden Moraine ~400 years older (at 11.8 ± 0.4 ka). Despite uncertainty relating to production rate choice, the relative timing of ice margin change within our chronology, such as the rapid retreat from fjord mouth to fjord head, remains a robust feature of our results.

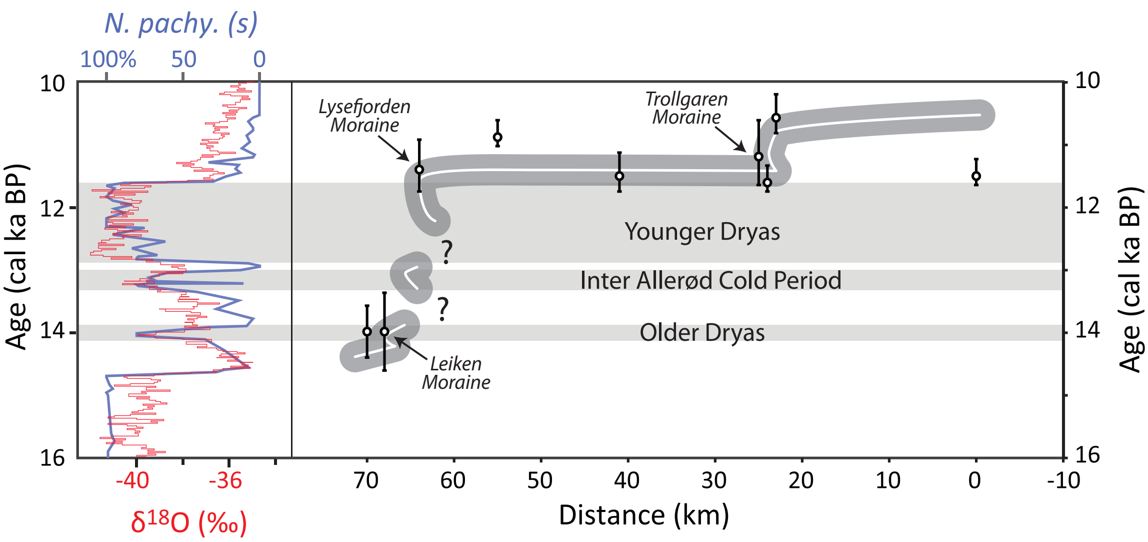

Figure 7. Time–distance diagram of the Scandinavian Ice Sheet in the Lysefjorden region, based on the ^{10}Be chronology presented here. The $\delta^{18}O$ record is from NGRIPNgrip Members (2004) and the *Neogloboquadrina pachyderma* (s) record is from Haflidason *et al.* (1995), here taken from Mangerud *et al.* (2013) who modified the time scale slightly.

Ice sheet history of Lysefjorden

Our ^{10}Be chronology, combined with mapping by Andersen (1954), reveals several pauses or re-advances during the overall deglaciation of the field area (Fig. 7). It seems clear that the multiple moraines in the Lyngsvatn area north of Lysefjorden, which Andersen (1954) mapped as a single system and included in his Lysefjorden Stage moraines of assumed Younger Dryas age, are rather composed of moraine ridges that represent at least two separate glacial events of considerable difference in age. The mean value (14.0 ± 0.6 ka) of the four ^{10}Be ages from the outer moraine ridge, that we here term the Leiken Moraine, indicates that this moraine formed well before the Younger Dryas, possibly during the Older Dryas. In contrast, the ages from the innermost ridge provide a significantly younger age (11.4 ± 0.4 ka), consistent with a late Younger Dryas age. Note that along the northern side of Lysefjorden, the inner ridge truncates the outer moraines, demonstrating that it was deposited during a younger re-advance. During a field excursion in the 1990 s, one of us (J. M.) observed several syn-sedimentary ice wedge casts in a gravel pit in the thick outwash gravel on top of the glacio-marine delta at Forsand, located in front of the Lysefjorden Moraine at the mouth of Lysefjorden (Fig. 3). Given that formation of ice wedges requires permafrost, it implies that the accumulation occurred during a cold period that we interpret as being the Younger Dryas.

The assumption that the ice front was located at the Lysefjorden Moraine during a late stage of the Younger Dryas is also supported by shoreline correlation. The relative sea-level history in western Norway is founded on several radiocarbon-dated isolation basins, and the pattern and timing of the shoreline displacement is reasonably well known (e.g. Anundsen, 1985; Helle, 2004; Lohne *et al.*, 2007; Romundset *et al.*, 2010). During the Allerød–Younger Dryas there was a relative sea-level rise of about 10 m, culminating at the end of the Younger Dryas and followed by a very rapid sea-level fall during the earliest Holocene due to strong and sustained glacio-isostatic uplift. The relative sea level of about 35 m a.s.l. indicated by the glacio-marine delta at Forsand correlates with the top of the Younger Dryas sea-level rise according to Anundsen (1985), also suggesting a Younger Dryas age of the moraine. We conclude that the Lysefjorden Moraine (11.4 ± 0.4 ka) was formed by a re-advance during the Younger Dryas, and that the rapid ice retreat through Lysefjorden coincides with warming at the Younger Dryas–Holocene transition, similar to the ice sheet history in Hardangerfjorden, 100 km to the north (Mangerud *et al.*, 2013).

Following deposition of the Lysefjorden Moraine, the ice margin retreated ~40 km through Lysefjorden, where it next deposited moraines near the fjord head, which may correlate with the Trollgaren Moraine that we dated at Jøsenfjordheia. Thus, the average age from beyond the Trollgaren Moraine (11.3 ± 0.5 ka) at Jøsenfjordheia may also provide the timing of ice retreat to the head of Lysefjorden. It seems likely that the Trollgaren Moraine was deposited synchronously with the Eldfjord–Osa Moraine, a widely traceable moraine that is found along fjord-heads in south-western Norway north of the field area and dated to ~11.1 ka (e.g. Mangerud *et al.*, 2013; Fig. 6).

Interestingly, our topographic-divide site appears to have become ice free ~11.6 ka, apparently before the retreat of ice from the Trollgaren Moraine, but the ages overlap within one standard deviation. One possibility is that the equilibrium-line altitude rose above the ice surface, and there was top-down ice sheet thinning. If this was the case, the high-elevation topographic-divide site might have become ice free earlier than valleys near the fjord heads.

Lateglacial ice sheet history throughout western Norway

To place our updated chronology into the context of the Lateglacial history of elsewhere around the Scandinavian Ice Sheet, we compiled previously published time–distance diagrams (Fig. 8), concentrating on the west coast of Norway facing the Norwegian Sea. We build on previous compilations (e.g. Mangerud, 1980; Andersen *et al.*, 1995; Nesje, 2009; Olsen *et al.*, 2013), and use updated chronological information where present with current radiocarbon calibration using CALIB 7.0 and the IntCal13 calibration curve. We emphasize that the quality of the stratigraphic and chronological basis for each curve varies. However, here we do not discuss the validity of each individual curve, but rather present the curves as the original authors did and point out the most robust features.

Our updated chronology of the Lysefjorden area has many similarities to the history of ice sheet fluctuations throughout western Norway. During most of the Bølling–Allerød period the ice sheet experienced net retreat. However, evidence for re-advances and/or end-moraine formation ~14 ka have been documented from throughout western Norway and have generally been correlated with the Older Dryas cold period (Fig. 8), although dating control is not precise enough to demand synchronicity. The Leiken Moraine dates to ~14.0 ka, and we thus correlate it to the same period. Stratigraphic sequences slightly north-west of our study area also show an advance around this time (Anundsen, 1972; Blystad and Anundsen, 1983; Fig. 8) and west of Bergen the Ulvøy Till (Mangerud, 1977) indicates that the corresponding ice advance reached the open ocean (Mangerud *et al.*, 2011). The Outer Coastal moraines in the Trondheim region (Reite, 1994) and the Skarpnes Moraine in the Tromsø region (Vorren and Plassen, 2002) also have a similar age (Fig. 8).

After the Older Dryas re-advance the ice sheet continued to retreat along the west coast. However, the sea-level history indicates that a renewed growth of the ice sheet soon started (Fig. 8). Following a relative sea-level fall due to the fast glacio-isostatic uplift during the early Allerød, relative sea level started to rise again during the middle Allerød, culminating at a local sea-level highstand around the end of the Younger Dryas (Anundsen, 1985; Lohne *et al.*, 2007). This local sea-level rise demands a halt in isostatic uplift (Fjeldskaar and Kanestrøm, 1980) and demonstrates the probability that the so-called 'Younger Dryas glacial re-advance' started well before the onset of the Younger Dryas. We emphasize that the sea-level rise dissipates near Nordfjord to the north and near the southern tip of Norway to the south (Fig. 1), suggesting that the largest glacial re-advances occurred in the area between (Lohne *et al.*, 2007). Such an early start (middle Allerød) for the ice sheet re-advance is also implied in most time–distance diagrams farther north (Fig. 8); however, glacier chronology in this interval generally is not well constrained with radiocarbon ages. In the Bergen (Mangerud *et al.*, 2013) and Andfjorden (Vorren and Plassen, 2002) areas, the ice front almost reached the Older Dryas ice margin position by the beginning of the Younger Dryas. As mentioned above, evidence from two areas near Lysefjorden indicate that till beyond Lysefjorden moraines dates to the latest Allerød or earliest Younger Dryas (Anundsen, 1977; Blystad and Anundsen, 1983), suggesting that the Younger Dryas ice position throughout south-western Norway was reached around the onset of the Younger Dryas.

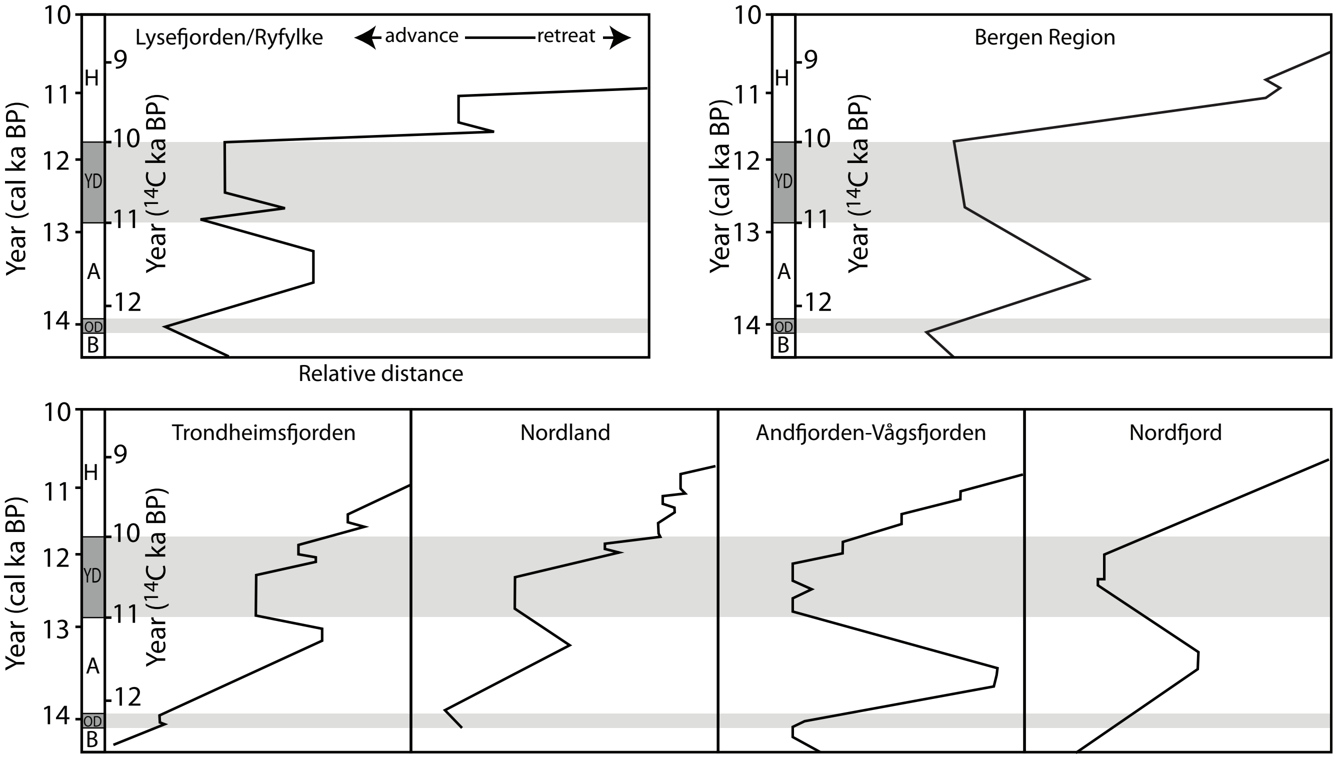

Figure 8. Time–distance diagrams of Scandinavian Ice Sheet margins along western Norway. The information for the Lysefjorden/Ryfylke diagram is from this study and from Blystad and Anundsen (1983; Fig. 4). Diagram from the Bergen region is from Mangerud *et al.* (2013), Nordfjord from Hjelstuen *et al.* (2009), Andfjorden–Vågsfjorden from Vorren and Plassen (2002) and Trondheimsfjorden and Nordland redrawn from Andersen *et al.* (1995). All *x* axes are relative distance, and do not scale with each other. H, Holocene; YD, Younger Dryas; A, Allerød; OD, Older Dryas; B, Bølling.

In most areas the moraines ascribed to the Younger Dryas are pronounced morphological features that can be traced along the entire western coast of Norway, and indeed around all of Fennoscandia (Fig. 1). In the Bergen–Hardangerfjorden region, several sites located inboard of the moraines contain shell-bearing tills and sub-till sediments dated to the Allerød (Mangerud *et al.*, 2013), indicating that the Allerød–Younger Dryas advance in this region was of significant magnitude. Outside of the Bergen–Hardangerfjorden area, radiocarbon ages from sediments overrun by ice only exist in a few areas (e.g. Hjelstuen *et al.*, 2009), and the re-advance is thus postulated on the basis of other evidence. It is possible that the moraines in some places were formed by only a small re-advance or even a halt during retreat. The advance to the Lysefjorden Moraine at the mouth of Lysefjorden overran previously deposited moraines (e.g. Leiken Moraine) that are present near Lyngsvatnet, implying a re-advance.

It has been noted for some time that moraines were formed at different times during the Younger Dryas, and the maximum ice extent, not always marked by end moraines, was asynchronous (Aarseth and Mangerud, 1974; Mangerud, 1980). In most areas the re-advance culminated during the early or middle Younger Dryas (Fig. 8), followed by retreat during the later part of the stadial. For example, in the Nordfjord, Trondheimsfjorden and Nordland regions (Fig. 1) available chronologies reveal that the ice sheet attained its maximum extent as early as ~12.9 cal ka BP, and retreated during the next few hundred years until ~12.4 cal ka BP (Andersen *et al.*, 1995; Hjelstuen *et al.*, 2009). Farther north, in the Andfjorden–Vågsfjorden area, the Tromsø–Lyngen Moraine was deposited between ~12.5 and ~12.0 cal ka BP (Vorren and Plassen, 2002). However, these chronologies are based on ^{14}C ages on marine shells and use a marine reservoir age of 400–440 ^{14}C years. Bondevik *et al.* (2006) showed that the marine reservoir correction may have been 200 years higher for this period. Regardless, in the Bergen–Hardangerfjorden area, the ice sheet reached the maximum extent close to the end of the Younger Dryas, after deposition of the Vedde Ash (12.1 ka; Bondevik and Mangerud, 2002; Lohne *et al.*, 2012). But even here the ice front was close to its maximum position during an early stage during the Younger Dryas with only a small, final growth at the end of the stadial (Mangerud *et al.*, 2013). In the Lysefjorden region, the ice margin history appears most similar to the Bergen–Hardangerfjorden region (Fig. 6).

Lateglacial climate history of western Norway

The timing of glacier advances during the Lateglacial in Norway seems to be aligned with its climate history. For example, temperature records from offshore Norway show a tight coupling with Greenland $\delta^{18}O$ records and reveal pronounced cooling not only during the Younger Dryas, but also during the Older Dryas and the Inter-Allerød Cold Period (Koç Karpuz and Jansen, 1992; Haflidason *et al.*, 1995). This climate pattern is also revealed in terrestrial climate records (e.g. Birks *et al.*, 1994; Birks and Ammann, 2000); thus, it is not surprising that glacial advances and moraine building events coincide with cold conditions revealed in these climate reconstructions. However, as described above, most time–distance diagrams reveal that the ice sheet was growing during the Allerød (Fig. 8). This ice growth could simply be because the Allerød was cooler than the Bølling, and that the Allerød was interrupted by cold periods, ultimately leading to cumulative ice growth. Ice growth during the Allerød also may have been favoured by a combination of mild temperatures and higher precipitation relative to extreme cold periods such as the Younger Dryas. Dokken *et al.* (2013)

suggested that the Scandinavian Ice Sheet should grow during mild parts of Dansgaard–Oeschger events due to more open adjacent seas as a source for precipitation. This idea is consistent with ice growth during the Allerød, and the suggestion that Bølling–Younger Dryas climate change could be a Dansgaard–Oeschger event (Mangerud *et al.*, 2010).

The underlying causes for the spatial differences in timing of ice margin fluctuations during the Allerød and Younger Dryas are not obvious. Some climate records reveal that the most stable and coldest conditions took place during the early Younger Dryas (Isarin and Bohncke, 1999; Lane *et al.*, 2013), with a slight warming through the Younger Dryas revealed by steadily increasing $\delta^{18}O$ values (NGRIP Members, 2004). This could explain the pattern of most ice margins reaching their maximum during the early Younger Dryas and subsequent retreat during the end of the Younger Dryas. An explanation for the later maximum in the Bergen–Lysefjorden area could be the topographic configuration. In this part of Norway, high mountain plateaus reside near the coast, which could serve as local accumulation zones for ice growth during the Younger Dryas. Elsewhere along the western coast of Norway, for example between Nordfjord and Trondheimsfjorden (Fig. 1), there are narrow alpine peaks, and inboard of Trondheimsfjorden there are wide lowlands (Mangerud, 1980). Another factor that has been proposed is the influence of spatial gradients in precipitation, controlled by south-westerly winds and more open water to the south (Mangerud *et al.*, 2011).

Summary and conclusion

We have updated the Lateglacial chronology of the Scandinavian Ice Sheet history in the Lysefjorden area, south-western Norway. Our ^{10}Be chronology, using a local ^{10}Be production rate, suggests that moraines in the Lysefjorden area that were previously thought to be of Younger Dryas age instead represent ice sheet fluctuations spanning from the Older Dryas (~14.0 ka) to the late Younger Dryas (~11.4 ka). However, this chronology would become ~4% older when using the Arctic-wide ^{10}Be production rate.

The Scandinavian Ice Sheet retreated to the Lysefjorden region by ~14.0 ka and subsequently deposited the Leiken Moraine ~14.0 ka. The Lysefjorden Moraine was deposited during the late Younger Dryas, and an undated moraine was deposited between ~14.0 and ~11.4 ka. The Lysefjorden Moraine was deposited during an advance that followed an episode of retreat of unknown magnitude. Following deposition of the Lysefjorden Moraine, the ice margin retreated rapidly through Lysefjorden, and final ice retreat from the head of the fjord occurred by ~10.7 ka. The ^{10}Be ages of ~11.6 ka from the topographic divide in south-central Norway leave open the possibility for top-down ice sheet wastage, such that parts of the high central uplands became ice free before some outlet glacier systems.

In the context of the Lateglacial history of Norway, the history of Lysefjorden is most similar to the Bergen–Hardangerfjorden region where an ice advance beginning during the middle Allerød culminated during the end of the Younger Dryas. Elsewhere, the Allerød/Younger Dryas advance culminated during the early to middle Younger Dryas. The reason for the spatio-temporal complexity of western Scandinavian Ice Sheet fluctuations during the Lateglacial is currently unknown.

Acknowledgements. We thank Stefan Truex for assistance with laboratory work, Susan Zimmerman and Robert Finkel for providing exceptional ^{10}Be AMS measurements, Lundin Norway AS for funding of the ^{10}Be dating, and the Leiv Eiriksson Mobility Programme of the Research Council of Norway for travel support. We acknowledge Nicolaj Larsen and Anders Schomacker for helpful reviews of the manuscript. This manuscript is dedicated to the late Bjørn Andersen, who encouraged this work to take place in his Master's thesis field area of 60 years ago.

Abbreviation. AMS, accelerator mass spectrometry

References

Aarseth I, Mangerud J. 1974. Younger Dryas end moraines between Hardangerfjorden and Sognefjorden, Western Norway. *Boreas* **3**: 3–22.

Andersen BG. 1954. Randmorener i sørvest Norge. *Norsk Geografisk Tidsskrift* **14**: 279–342.

Andersen BG, Mangerud J, Sørensen R, *et al.* 1995. Younger Dryas ice-marginal deposits in Norway. *Quaternary International* **28**: 147–169.

Anundsen K. 1972. Glacial chronology in parts of southwestern Norway. *Norges Geologiske Undersøkelse* **280**: 1–24.

Anundsen K. 1977. Radiocarbon datings and glacial striae from the inner part of Boknfjord area, South Norway. *Norsk Geografisk Tidsskrift* **31**: 41–54.

Anundsen K. 1985. Changes in shore-level and ice-front position in Late Weichsel and Holocene, Southern Norway. *Norsk Geografisk Tidsskrift* **39**: 205–225.

Balco G, Stone J, Lifton N, *et al.* 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology* **3**: 174–195.

Balco G, Briner J, Finkel RC, *et al.* 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology* **4**: 93–107.

Birks HH, Ammann B. 2000. Two terrestrial records of rapid climatic change during the glacial–Holocene transition (14,000–9,000 calendar years B.P.) from Europe. *Proceedings of the National Academy of Sciences* **97**: 1390–1394.

Birks HH, Paus AA, Svendsen JI, *et al.* 1994. Late Weichselian environmental change in Norway, including Svalbard. *Journal of Quaternary Science* **9**: 133–145.

Blystad R, Anundsen K. 1983. Late Weichselian stratigraphy at Hielmeland, Southwest Norway. *Norsk Geologisk Tidsskrift* **63**: 277–287.

Blystad P, Selsing L. 1988. Deglaciation chronology in the mountain area between Suldal and Setesdal, southwestern Norway. *Norges Geologiske Undersøkelse* **410**: 67–92.

Bondevik S, Mangerud J. 2002. A calendar age estimate of a very late Younger Dryas ice sheet maximum in western Norway. *Quaternary Science Reviews* **21**: 1661–1676.

Bondevik S, Mangerud J, Birks HH, *et al.* 2006. Changes in North Atlantic radiocarbon reservoir ages during the Allerød and Younger Dryas. *Science* **312**: 1514–1517.

Briner JP, Bini AC, Anderson RS. 2009. Rapid early Holocene retreat of a Laurentide outlet glacier through an Arctic fjord. *Nature Geoscience* **2**: 496–499.

Clark PU, Alley R, Pollard D. 1999. Northern Hemisphere ice-sheet influences on global climate change. *Science* **286**: 1104–1111.

Clark PU, Dyke AS, Shakun JD, *et al.* 2009. The Last Glacial Maximum. *Science* **325**: 710–714.

Dokken TM, Nisancioglu KH, Li C, *et al.* 2013. Dansgaard–Oeschger cycles: interactions between ocean and sea ice intrinsic to the Nordic seas. *Paleoceanography* **28**: 491–502.

Fjeldskaar W, Kanestrøm R. 1980. Younger Dryas geoid-deformation caused by deglaciation in Fennoscandia. In *Earth Rheology, Isostasy and Eustasy*, Mörner N-A (ed.). Wiley: Chichester, UK; 569–574.

Goehring BM, Brook EJ, Linge H, *et al.* 2008. Beryllium-10 exposure ages of erratic boulders in southern Norway and implications for the history of the Fennoscandian Ice Sheet. *Quaternary Science Reviews* **27**: 320–336.

Goehring BM, Lohne ØS, Mangerud J, *et al.* 2012a. Late Glacial and Holocene ^{10}Be production rates for western Norway. *Journal of Quaternary Science* **27**: 89–96.

Goehring BM, Lohne ØS, Mangerud J, *et al.* 2012b. Erratum: Late Glacial and Holocene ^{10}Be production rates for western Norway. *Journal of Quaternary Science* **27**: 544.

Gosse JC, Phillips FM. 2001. Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Reviews* **20**: 1475–1560.

Haflidason H, Sejrup H-P, Klitgaard Kristensen D, *et al.* 1995. Coupled response of the late glacial climatic shifts of northwest Europe reflected in Greenland ice cores: evidence from the northern North Sea. *Geology* **23**: 1059–1062.

Helle SK. 2004. Sequence stratigraphy in a marine moraine at the head of Hardangerfjorden, western Norway: evidence for a high-frequency relative sea-level cycle. *Sedimentary Geology* **164**: 251–281.

Hjelstuen BO, Haflidason H, Sejrup HP, *et al.* 2009. Sedimentary processes and depositional environments in glaciated fjord systems – evidence from Nordfjord, Norway. *Marine Geology* **258**: 88–99.

Isarin RFB, Bohncke SJP. 1999. Mean July temperatures during the Younger Dryas in northwestern and central Europe as inferred from climate indicator plant species. *Quaternary Research* **51**: 158–173.

Knudsen CG. 2006. *Glacier dynamics and Lateglacial environmental changes-evidences from SW Norway and Iceland*. PhD Thesis, Department of Earth Science, University of Bergen.

Koç Karpuz N, Jansen E. 1992. A high-resolution diatom record of the last deglaciation from the SE Norwegian Sea: documentation of rapid climatic changes. *Paleoceanography* **7**: 499–520.

Lal D. 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* **104**: 424–439.

Lane CS, Brauer A, Blockley SPE, *et al.* 2013. Volcanic ash reveals time-transgressive abrupt climate change during the Younger Dryas. *Geology* **41**: 1251–1254.

Lohne ØS, Bondevik S, Mangerud J, *et al.* 2007. Sea-level fluctuations imply that the Younger Dryas ice-sheet expansion in western Norway commenced during the Allerød. *Quaternary Science Reviews* **26**: 2128–2151.

Lohne ØS, Mangerud J, Svendsen JI. 2012. Timing of the Younger Dryas glacial maximum in western Norway. *Journal of Quaternary Science* **27**: 81–88.

Lohne ØS, Mangerud J, Birks HH. 2013. Precise ^{14}C ages of the Vedde and Saksunarvatn ashes and the Younger Dryas boundaries from western Norway and their comparison with the Greenland Ice Core (GICC05) chronology. *Journal of Quaternary Science* **28**: 490–500.

Mangerud J. 1977. Late Weichselian marine sediments containing shells, foraminifera, and pollen, at Ågotnes, western Norway. *Norsk Geologisk Tidsskrift* **57**: 23–54.

Mangerud J. 1980. Ice-front variations of different parts of the Scandinavian Ice Sheet, 13,000–10,000 years B.P. In *Studies in the Lateglacial of North–West Europe: Including Papers Presented at a Symposium of the Quaternary Research Association held at University College London, January 1979*, Lowe JJ, Gray JM, Robinson JE (Eds). Pergamon Press: Oxford; 23–30.

Mangerud J, Gulliksen S, Larsen E. 2010. ^{14}C-dated fluctuations of the western flank of the Scandinavian Ice Sheet 45–25 kyr BP compared with Bølling-Younger Dryas fluctuations and Dansgaar-Oeschger events in Greenland. *Boreas* **39**: 328–342.

Mangerud J, Gyllencreutz R, Lohne Ø, *et al.* 2011. Glacial history of Norway. In *Quaternary Glaciations – Extent and Chronology*, Ehlers J, Gibbard P, Hughes P (eds). Elsevier: Amsterdam. pp. 279–298.

Mangerud J, Goehring BM, Lohne ØS, *et al.* 2013. Collapse of marine-based outlet glaciers from the Scandinavian Ice Sheet. *Quaternary Science Reviews* **67**: 8–16.

NGRIP Project Members. 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* **431**: 147–151.

Nesje A. 2009. Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia. *Quaternary Science Reviews* **28**: 2119–2136.

Nishiizumi K, Imamura M, Caffee M, *et al.* 2007. Absolute calibration of ^{10}Be AMS standards. *Nuclear Instruments and Methods* **258**: 403–413.

Olsen L, Sveian H, Bergstrøm B, *et al.* 2013. Quaternary glaciations and their variations in Norway and on the Norwegian continental shelf. In *Quaternary Geology of Norway*, Olsen L, Fredin O, Olesen O (Eds). *Geological Survey of Norway Special Publication* **13**: 27–78.

Reite AJ. 1994. Weichselian and Holocene geology of Sr-Trøndelag and adjacent parts of Nord-Trøndelag county, Central Norway. *Norges Geologiske Undersøkelse* **426**: 1–30.

Romundset A, Lohne ØS, Mangerud J, *et al.* 2010. The first Holocene relative sea-level curve from the middle part of Hardangerfjorden, western Norway. *Boreas* **39**: 87–104.

Rood DH, Hall S, Guilderson TP, *et al.* 2010. Challenges and opportunities in high precision Be-10 measurements at CAMS. *Nuclear Instruments and Methods B: Beam Interactions with Material and Atoms* **268**: 730–732.

Sejrup HP, Landvik JY, Larsen E, *et al.* 1998. The Jæren area, a border zone of the Norwegian Channel ice stream. *Quaternary Science Reviews* **17**: 801–812.

Staiger J, Gosse J, Toracinta R, *et al.* 2007. Atmospheric scaling of cosmogenic nuclide production: climate effect. *Journal of Geophysical Research* **112**: B02205.

Stone J. 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* **105**: 23753–23759.

Vorren TO, Plassen L. 2002. Deglaciation and palaeoclimate of the Andfjord-Vågsfjord area, North Norway. *Boreas* **31**: 97–125.

Worsley P. 2006. Jens Esmark, Vassryggen and early glacial theory in Britain. *Mercian Geologist* **16**: 161–172.

Young NE, Briner JP, Stewart HAM, *et al.* 2011. Response of Jakobshavn Isbrae, Greenland, to Holocene climate change. *Geology* **39**: 131–134.

Young NE, Briner JP, Rood DH, *et al.* 2013a. Age of the Fjord Stade moraines in the Disko Bugt region, western Greenland, and the 9.3 and 8.2 ka cooling events. *Quaternary Science Reviews* **60**: 76–90.

Young NE, Schaefer JM, Briner JP, *et al.* 2013b. A ^{10}Be production-rate calibration for the Arctic. *Journal of Quaternary Science* **28**: 515–526.

